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(54) **NITRIDE SEMICONDUCTOR LIGHT-EMITTING ELEMENT**

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H01L 31/00	(2006.01)

(Continued)

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CPC ***H01L 33/325*** (2013.01); ***H01L 33/16*** (2013.01)

(58) **Field of Classification Search**
USPC 257/E33.012, 103, 13
See application file for complete search history.

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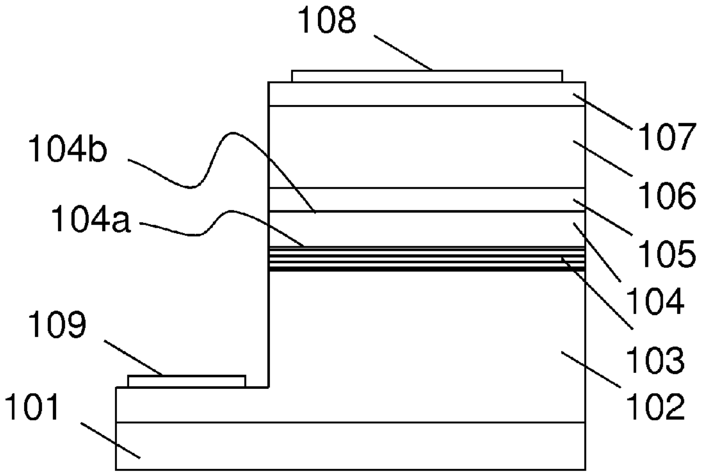
(57) **ABSTRACT**

The present invention improves luminous efficiency of a nitride semiconductor light-emitting element. In the nitride semiconductor light-emitting element, a non-polar or semi-polar $Al_{x2}In_{y2}Ga_{z2}N$ layer having a thickness of t1 is interposed between the $Al_{x1}In_{y1}Ga_{z1}N$ layer included in the p-type nitride semiconductor layer and the active layer ($0<x2\leq1$, $0\leq y2<1$, $0<z2<1$, $x2+y2+z2=1$). The $Al_{x2}In_{y2}Ga_{z2}N$ layer has first and second interfaces located close to or in contact with the active layer and the $Al_{x1}In_{y1}Ga_{z1}N$ layer, respectively. The $Al_{x2}In_{y2}Ga_{z2}N$ layer has a hydrogen concentration distribution along its thickness direction in the inside thereof in such a manner that the hydrogen concentration is increased from the first interface to a thickness t2 (t2<t1), reaches a peak at the thickness t2, and is decreased from the thickness t2 to the second interface. Magnesium contained in the $Al_{x1}In_{y1}Ga_{z1}N$ layer is prevented from being diffused into the active layer to improve the luminous efficiency.

8 Claims, 11 Drawing Sheets



(51) **Int. Cl.**

H01L 33/32	(2010.01)
H01L 33/16	(2010.01)

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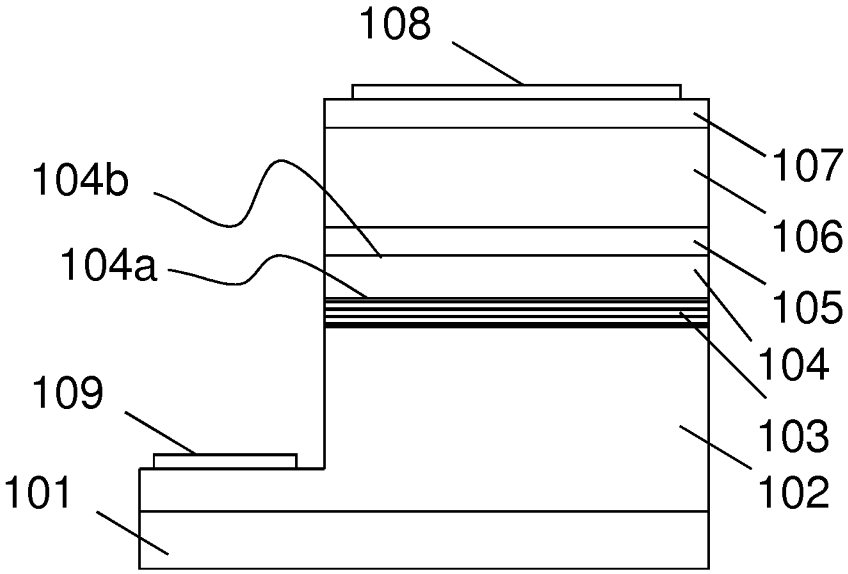
108
104b
107
106
104a
105
104
109
103
101
102

FIG. 1

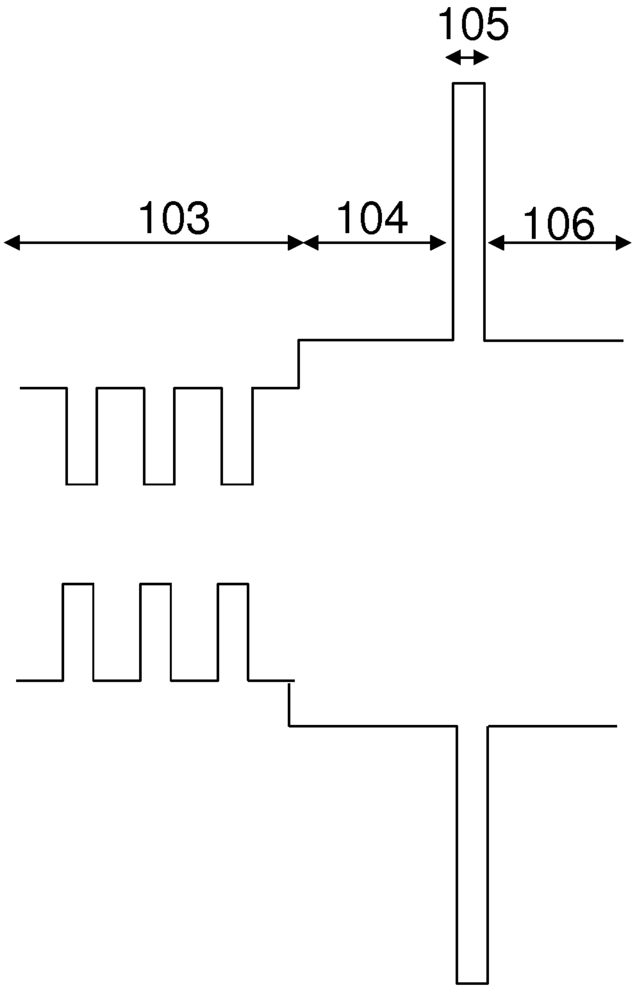
105
103
104
106

FIG. 2A

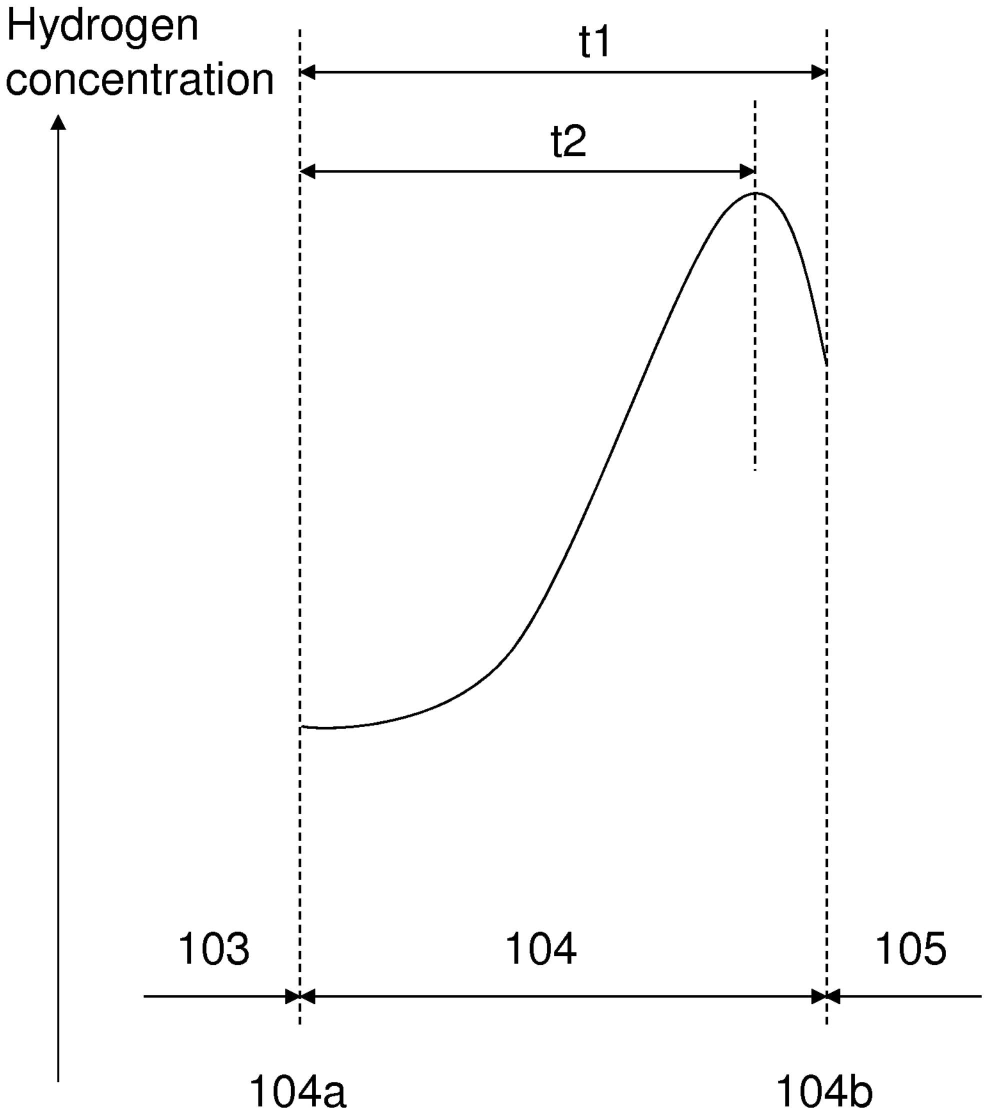

FIG. 2B

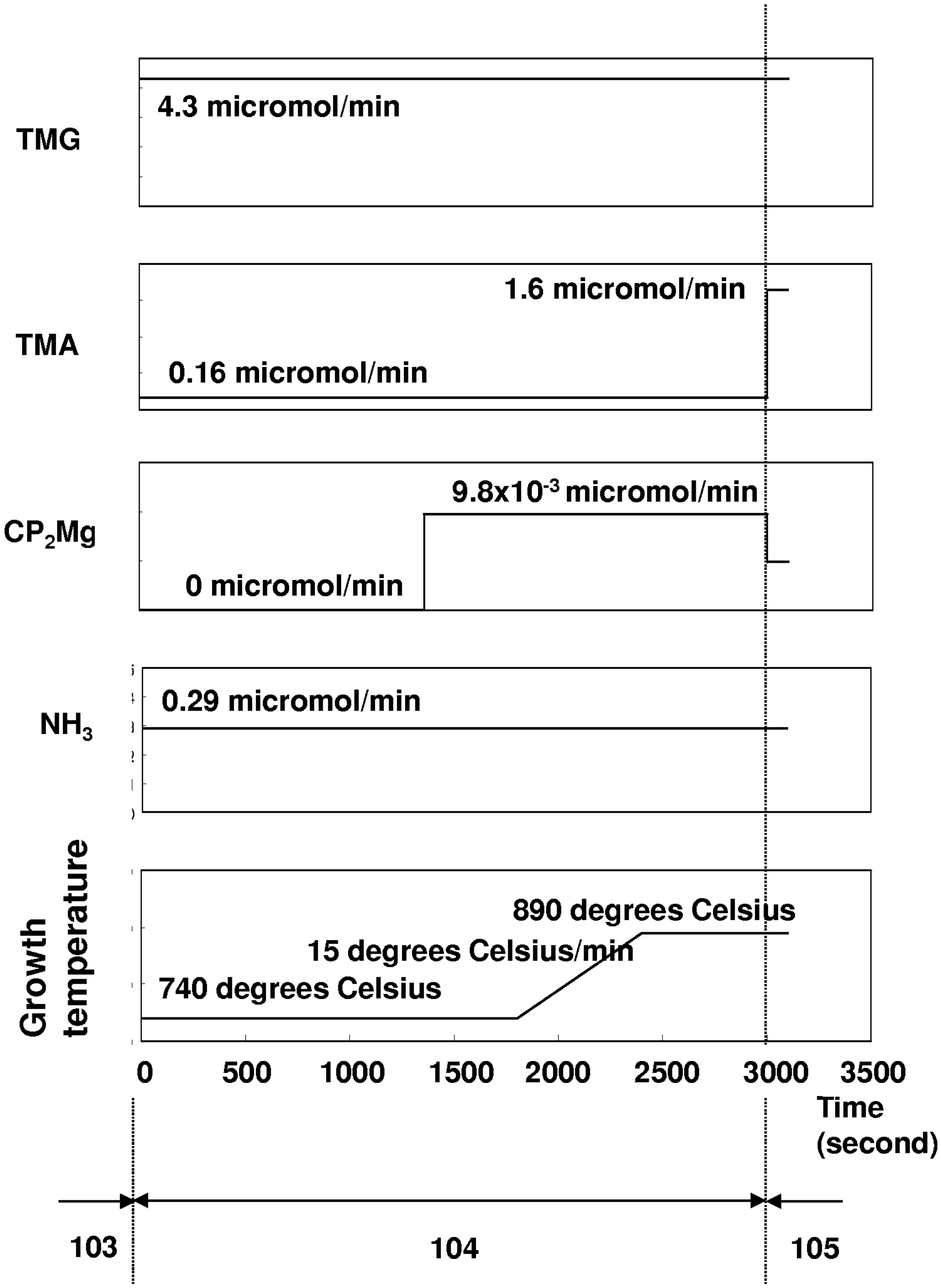
TMG
4.3 micromol/min
TMA
1.6 micromol/min
0.16 micromol/min
CP_2Mg
9.8x10^{-3} micromol/min
0 micromol/min
NH_3
0.29 micromol/min
Growth temperature
890 degrees Celsius
15 degrees Celsius/min
740 degrees Celsius
0
500
1000
1500
2000
2500
3000
3500
Time (second)
103
104
105

FIG. 3

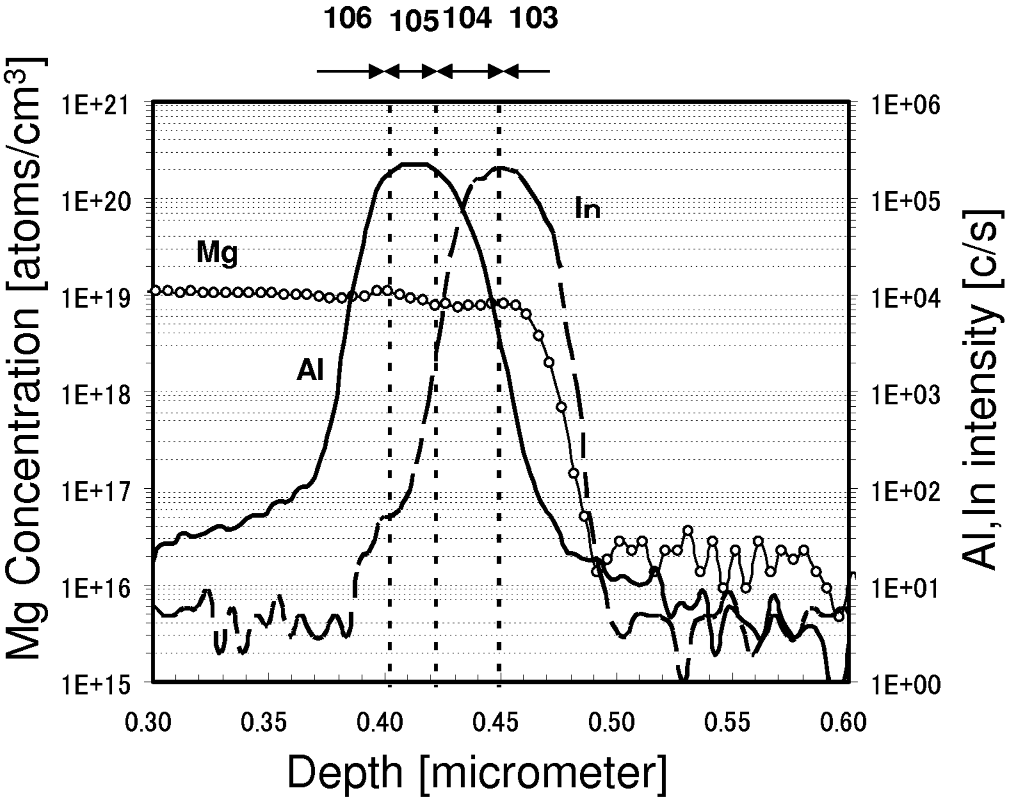
106
105
104
103
Mg Concentration [atoms/cm^3]
1E+21
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15
Al,In intensity [c/s]
1E+06
1E+05
1E+04
1E+03
1E+02
1E+01
1E+00
Mg
Al
In
0.30
0.35
0.40
0.45
0.50
0.55
0.60
Depth [micrometer]

FIG. 4A

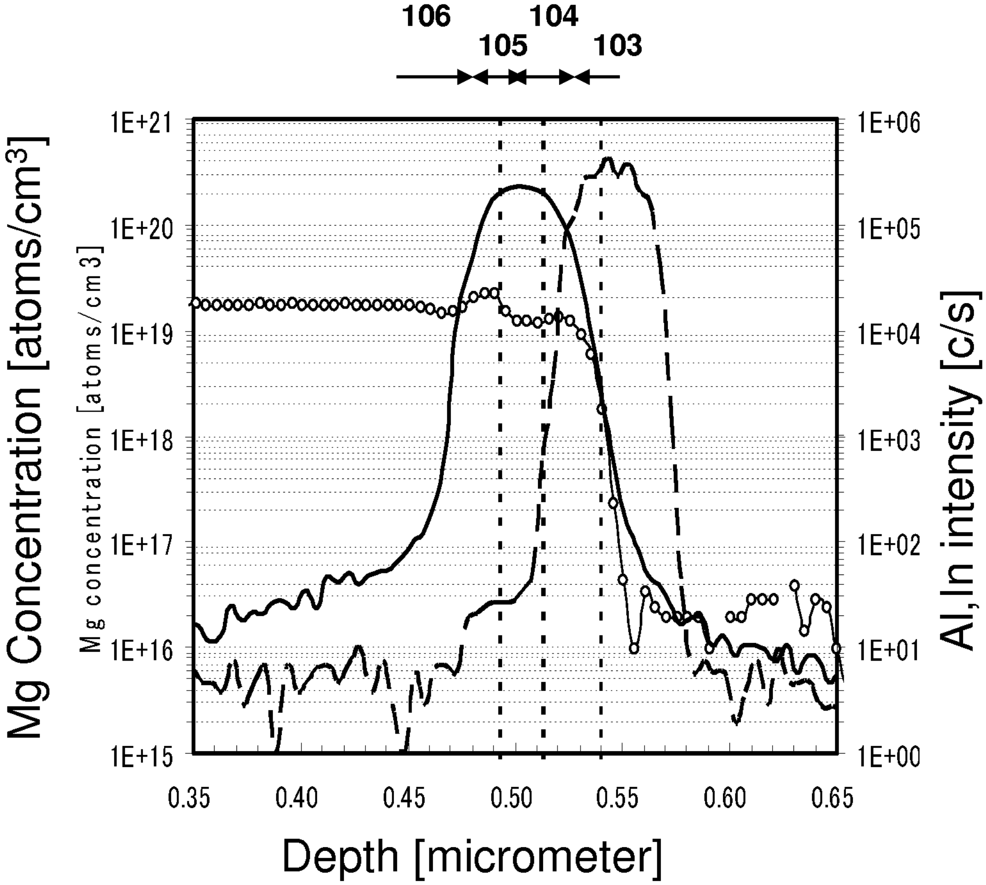
106
105
104
103
Mg Concentration [atoms/cm^3]
Mg concentration [atoms/cm3]
Al,In intensity [c/s]
1E+21
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15
1E+06
1E+05
1E+04
1E+03
1E+02
1E+01
1E+00
0.35
0.40
0.45
0.50
0.55
0.60
0.65
Depth [micrometer]

FIG. 4B

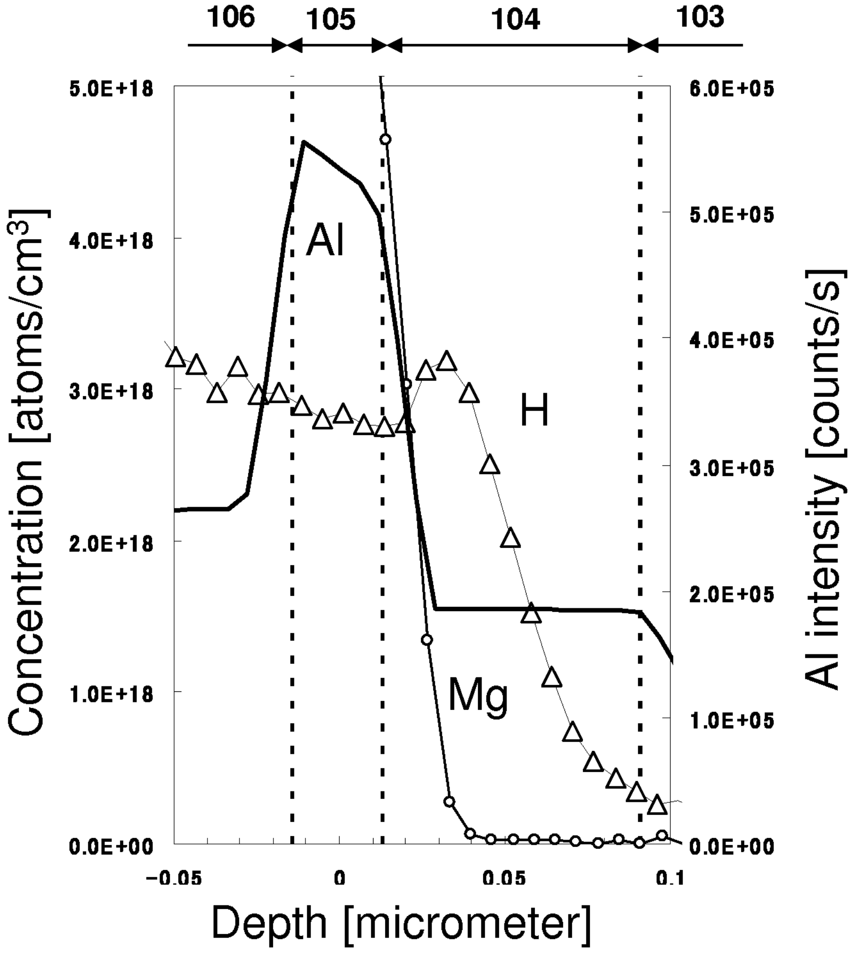
106
105
104
103
Concentration [atoms/cm^3]
5.0E+18
4.0E+18
3.0E+18
2.0E+18
1.0E+18
0.0E+00
Al intensity [counts/s]
6.0E+05
5.0E+05
4.0E+05
3.0E+05
2.0E+05
1.0E+05
0.0E+00
Al
H
Mg
−0.05
0
0.05
0.1
Depth [micrometer]

FIG. 5

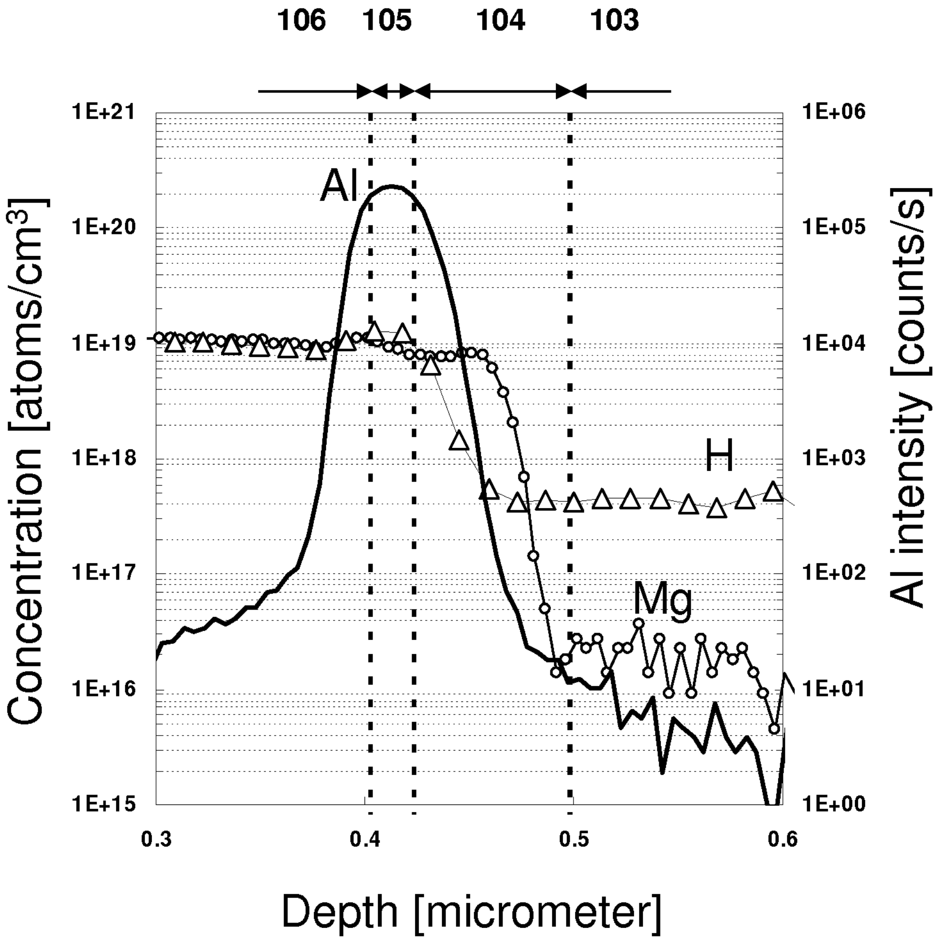
106
105
104
103
1E+21
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15
1E+06
1E+05
1E+04
1E+03
1E+02
1E+01
1E+00
Al
H
Mg
Concentration [atoms/cm3]
Al intensity [counts/s]
0.3
0.4
0.5
0.6
Depth [micrometer]

FIG.6

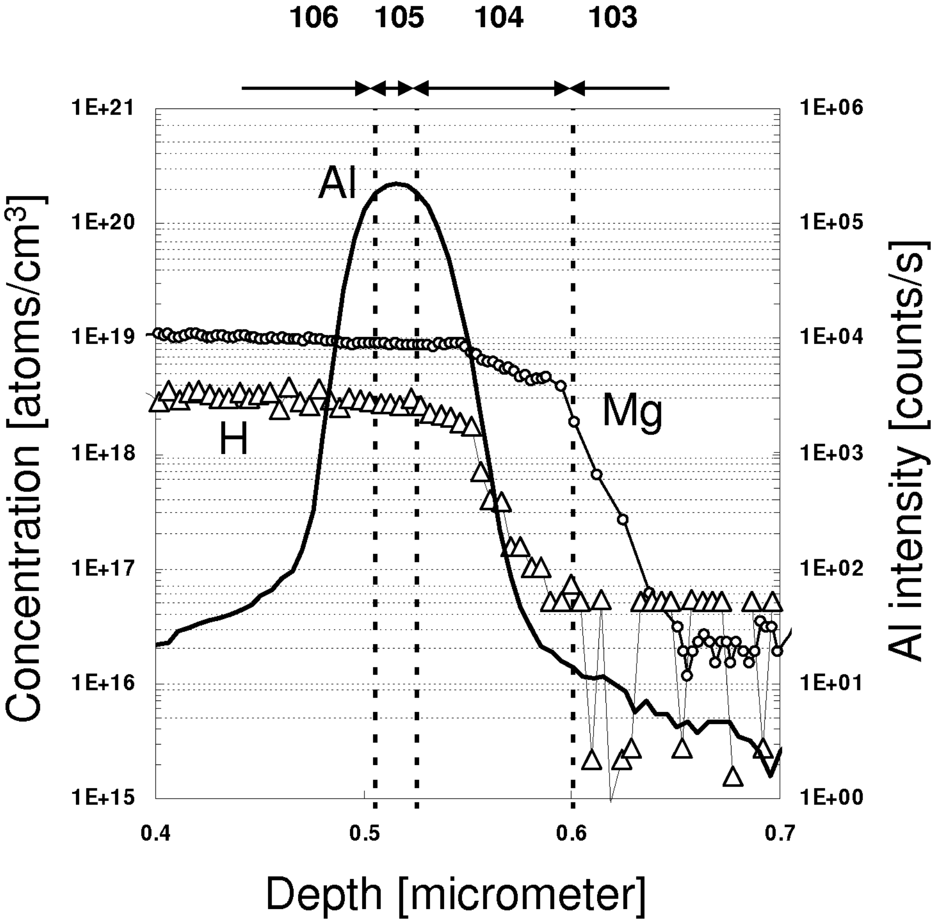
106
105
104
103
1E+21
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15
1E+06
1E+05
1E+04
1E+03
1E+02
1E+01
1E+00
Al
Mg
H
0.4
0.5
0.6
0.7
Concentration [atoms/cm^3]
Al intensity [counts/s]
Depth [micrometer]

FIG.7

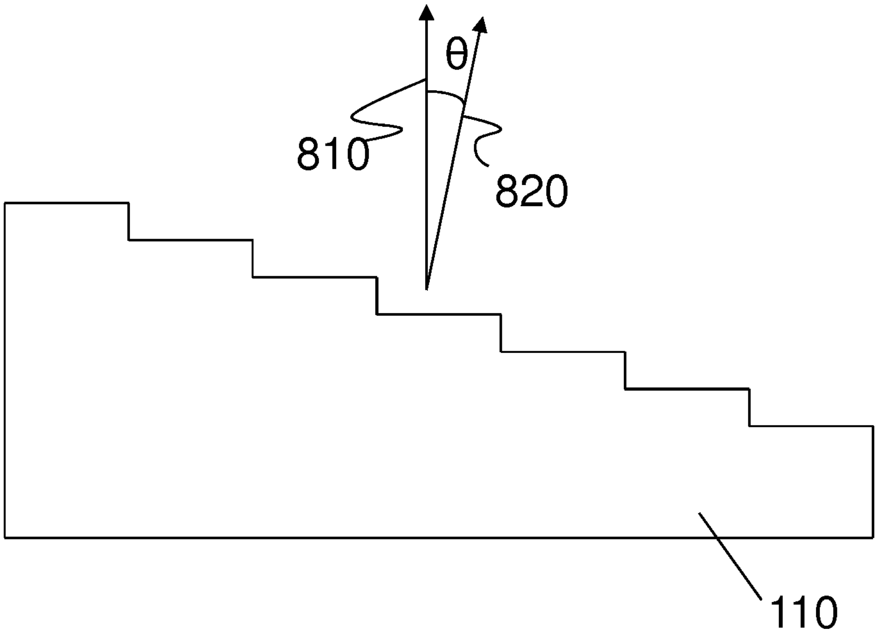
θ
810
820
110

FIG.8

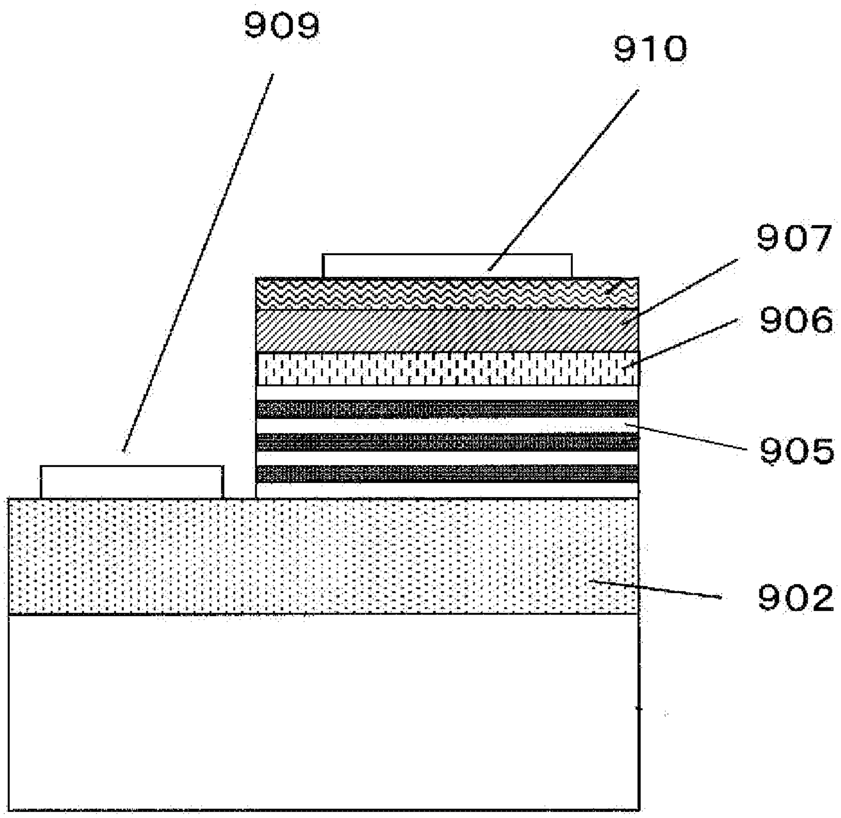
909
910
907
906
905
902

FIG. 9

NITRIDE SEMICONDUCTOR LIGHT-EMITTING ELEMENT

BACKGROUND

1. Technical Field

The present invention relates to a nitride semiconductor light-emitting element.

2. Description of the Related Art

Recently, a nitride semiconductor light-emitting element having a principal plane of an m-plane has been researched and developed actively to improve luminous efficiency. This is because a nitride semiconductor light-emitting element having a principal plane of an m-plane is free from piezoelectric field, which decreases luminous efficiency. Hereinafter, a nitride semiconductor light-emitting element having a principal plane of an m-plane is referred to as "m-plane nitride semiconductor light-emitting element".

United States Pre-Grant Patent Application Publication 2013/0234110 discloses an m-plane nitride semiconductor light-emitting element. As shown in FIG. **9**, the m-plane nitride semiconductor light-emitting element comprises an n-side electrode **909**, an n-type nitride semiconductor layer **902**, an active layer **905**, a p-type nitride semiconductor layer **907** and a p-side electrode **910**. A voltage is applied between the n-side electrode **909** and the p-side electrode **910** to emit light from the active layer **905**.

A p-type AlGaN electron block layer **906** is interposed between the p-type nitride semiconductor layer **907** and the active layer **905**.

The p-type nitride semiconductor layer **907** and the p-type AlGaN electron block layer **906** contain magnesium as a dopant.

SUMMARY

When an m-plane nitride semiconductor light-emitting element is subjected to annealing, magnesium contained in the p-type nitride semiconductor layer **907** and in the p-type AlGaN electron block layer **906** may be diffused into the active layer **905**. This diffusion phenomenon of magnesium also occurs when a voltage is applied to the m-plane nitride semiconductor light-emitting element.

Magnesium which has diffused into the active layer **905** reduces luminous efficiency of the active layer **905**.

The present invention provides a nitride semiconductor light-emitting element comprising:

an n-side electrode;

a p-side electrode;

an n-type nitride semiconductor layer electrically connected to the n-side electrode;

a p-type nitride semiconductor layer electrically connected to the p-side electrode; and

an active layer interposed between the n-type nitride semiconductor layer and the p-type nitride semiconductor layer; wherein

the p-type nitride semiconductor layer comprises an $Al_{x1}In_{y1}Ga_{z1}N$ layer ($0<x1\leq 1$, $0\leq y1<1$, $0\leq z1<1$, $x1+y1+z1=1$),

an $Al_{x2}In_{y2}Ga_{z2}N$ layer is interposed between the $Al_{x1}In_{y1}Ga_{z1}N$ layer and the active layer ($0<x2\leq 1$, $0\leq y2<1$, $0<z2<1$, $x2+y2+z2=1$),

the n-type nitride semiconductor layer, the active layer, the p-type nitride semiconductor layer, the $Al_{x1}In_{y1}Ga_{z1}N$ layer and the $Al_{x2}In_{y2}Ga_{z2}N$ layer are each formed of a non-polar or semi-polar nitride semiconductor,

the $Al_{x1}In_{y1}Ga_{z1}N$ layer has a higher bandgap than the $Al_{x2}In_{y2}Ga_{z2}N$ layer,

the $Al_{x2}In_{y2}Ga_{z2}N$ layer has a first interface and a second interface,

the first interface is located close to or in contact with the active layer,

the second interface is located close to or in contact with the $Al_{x1}In_{y1}Ga_{z1}N$ layer,

the $Al_{x2}In_{y2}Ga_{z2}N$ layer has a thickness t1,

the $Al_{x2}In_{y2}Ga_{z2}N$ layer has a hydrogen concentration distribution along its thickness direction in the inside thereof in such a manner that the hydrogen concentration is increased from the first interface to a thickness t2 ($t2<t1$), reaches a peak at the thickness t2, and is decreased from the thickness t2 to the second interface.

Magnesium contained in the $Al_{x1}In_{y1}Ga_{z1}N$ layer is prevented from being diffused into the active layer. For this reason, the luminous efficiency is improved.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a cross-sectional view of a nitride semiconductor light-emitting element according to the present embodiment.

FIG. **2**A shows bandgaps of the active layer **103**, the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** and the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105**.

FIG. **2**B shows a hydrogen concentration distribution in the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** along the thickness direction thereof.

FIG. **3** shows an example of an epitaxial growth profile according to the procedure P1.

FIG. **4**A shows a SIMS analysis result of the nitride semiconductor light-emitting element according to the comparative example 1.

FIG. **4**B shows a SIMS analysis result of the nitride semiconductor light-emitting element according to the reference example 1.

FIG. **5** shows a SIMS analysis result of the nitride semiconductor light-emitting element according to the example 1.

FIG. **6** shows a SIMS analysis result in the comparative example 1 before the p-type dopant, namely, magnesium, was activated by annealing.

FIG. **7** shows a SIMS analysis result in the comparative example 5 after the p-type dopant was activated by annealing.

FIG. **8** shows a substrate **101** having an off-angle θ.

FIG. **9** shows an m-plane nitride semiconductor light-emitting element disclosed in International Publication No. 2012/140844.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Embodiments of the present invention will be described below with reference to the drawings.

As shown in FIG. **1**, a nitride semiconductor light-emitting element according to the present embodiment comprises an n-side electrode **109**, a p-side electrode **108**, an n-type nitride semiconductor **102** electrically connected to the n-side electrode **109**, a p-type nitride semiconductor **106** electrically connected to the p-side electrode **108**, and an active layer **103** interposed between the n-type nitride semiconductor **102** and the p-type nitride semiconductor **106**.

The p-type nitride semiconductor layer **106** comprises a p-type $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** ($0<x1\leq 1$, $0\leq y<1$, $0\leq z1<1$, $x1+y1+z1=1$). Desirably, the value of y1 is equal to 0. Desirably, the value of x1 is not less than 0.1 and not more than 0.3.

The $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** functions as an overflow-suppression layer. In more detail, electrons are supplied from the n-side electrode **109** to the active layer **103**. When an excess amount of the electrons are supplied to the active layer **103**, a portion of the excess amount of the electrons travels through the active layer **103** toward the p-side electrode **108**. However, the excess amount of the electrons thus supplied to the active layer **103** are blocked by the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** to return to the active layer **103**. As understood from this description, since the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** blocks the excess amount of the electrons supplied from the n-side electrode **109** to the active layer **103**, the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** is referred to as an overflow-suppression layer.

The p-type $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** contains magnesium as a dopant.

The n-type nitride semiconductor layer **102**, the active layer **103**, the p-type nitride semiconductor layer **106** and the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** are each formed of a non-polar or semi-polar nitride semiconductor. Desirably, these layers are each formed of an m-plane nitride semiconductor.

The $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** ($0<x2\leq1$, $0\leq y2<1$, $0<z2<1$, $x2+y2+z2=1$) is interposed between the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** and the active layer **103**. This $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is also formed of a non-polar or semi-polar nitride semiconductor. Desirably, the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is also formed of an m-plane nitride semiconductor.

The $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** contains aluminum. In other words, the value of x2 is more than zero. The value of x2 must not be zero. In case where the layer **104** does not contains aluminum, the magnesium contained in the p-type $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** is not prevented sufficiently from being diffused into the active layer **103**, as described in more detail in the comparative examples 1-4, which are described later. Desirably, the value of y2 is equal to 0. Desirably, the value of x2 is not less than 0.001 and not more than 0.10.

The $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** has a higher bandgap than the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**. In case where the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** has a higher bandgap than the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105**, the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** does not function as the overflow-suppression layer.

The $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** has a first interface **104***a* and a second interface **104***b*. In FIG. **1**, the first interface **104***a* is in contact with the active layer **103**. The second interface **104***b* is in contact with the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105**.

A nitride semiconductor layer (not shown) may be interposed between the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** and the active layer **103**. In this case, the first interface **104***a* is in contact with the nitride semiconductor thus interposed. Similarly, a different nitride semiconductor layer (not shown) may be interposed between the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** and the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105**. In this case, the second interface **104***b* is in contact with the different nitride semiconductor layer thus interposed. In other words, in this case, the first interface **104***a* and the second interface **104***b* are close to the active layer **103** and the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105**, respectively.

The $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** has a thickness t1. Desirably, the thickness t1 is not less than 20 nanometers and not more than 100 nanometers. In a case where the thickness t1 is less than 20 nanometers, magnesium contained in the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** may not be prevented sufficiently from being diffused into the active layer **103**. This is because the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is too thin. On the other hand, in a case where the thickness t1 is more than 100 nanometers, the luminous efficiency of the nitride semiconductor light-emitting element may be decreased. This is because a thicker $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** has a greater resistance.

More desirably, the thickness t1 is not less than 30 nanometers and not more than 75 nanometers.

FIG. **2**A shows a bandgap of the active layer **103**, the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** and the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105**. FIG. **2**B shows a hydrogen concentration distribution in the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** along the thickness direction thereof.

As shown in FIG. **2**B, the hydrogen concentration is increased from the first interface **104***a* to a thickness t2 (t2<t1). Desirably, the hydrogen concentration is increased monotonically. The hydrogen concentration reaches a peak at the thickness t2. The hydrogen concentration is decreased from the thickness t2 to the second interface **104***b*. Desirably, the hydrogen concentration is decreased monotonically.

Magnesium contained in the p-type nitride semiconductor layer is diffused greater in an m-plane nitride semiconductor light-emitting element than in a conventional c-plane nitride semiconductor light-emitting element, as understood from the comparison between the example 1 (FIG. **4**A) and the reference example 1 (FIG. **4**B), both of which are described later. For this reason, the problem that magnesium decreases the luminous efficiency of the active layer **103** is more serious in an m-plane nitride semiconductor light-emitting element than in a conventional c-plane nitride semiconductor light-emitting element.

Also when a voltage is applied between the p-side electrode **108** and the n-side electrode **109**, magnesium contained in the p-type nitride semiconductor layer **106** is diffused into the active layer **103**.

As is clear from the examples **1-3**, which are described later, the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** prevents magnesium from being diffused into the active layer **103**. For this reason, it is difficult for magnesium to reach the active layer **103**. In this way, the luminous efficiency of the active layer **103** is improved.

In particular, as shown in FIG. **5**, which described later, it is desirable that magnesium is prevented from being diffused in such a manner that the magnesium concentration at the first interface **104***a* is not more than 1.0×10^{17} atoms/cm^3.

The reason why the nitride semiconductor light-emitting element according to the present embodiment has the improved luminous efficiency is described in the following items (a) and (b).

(a) The $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** contains aluminum.

(b) The $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** has a peak of the hydrogen concentration at the thickness t2.

First, the item (a) is described in more detail.

As explained in C. Stampfl et. al., "Doping of $Al_xGa_{1-x}N$ alloys", Material science and Engineering B59, 253-257 (1999), magnesium contained in an AlGaN layer is more unstable than magnesium contained in a GaN layer. For this reason, compared to a case where the layer **104** is a nitride semiconductor layer which does not contain aluminum, magnesium is poorly diffused from the $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** to the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**, which contains aluminum.

Next, the item (b) is described. As described in R. R. Wixom et. al. "Binding of the N interstitial with neutral MgH in p-type GaN investigated with density functional theory", PHYSICAL REVIEW B 72, 024114 (2005), an Mg—H bond is stable in a nitride semiconductor. For this reason, even when magnesium is diffused into the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**, magnesium is bound to hydrogen contained in the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**.

The hydrogen concentration is increased in the section from the second interface **104***b* to the thickness t2, namely, the peak position of the hydrogen concentration. See FIG. **2**B. For this reason, it would be significantly difficult for magnesium to be diffused into the active layer **103** in the section from the second interface **104***b* to the thickness t2, namely, the peak position of the hydrogen concentration. This is because a stable Mg—H bond is formed in this section. In other words, the hydrogen concentration distribution where the hydrogen concentration reaches the peak at the thickness t2 prevents magnesium from being diffused into the active layer **103**. In this way, the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** having the hydrogen concentration distribution where the hydrogen concentration reaches the peak at the thickness t2 functions as a layer which captures magnesium.

In case where the hydrogen concentration in the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** decreases monotonically from the second interface **104***b* to the first interface **104***a* in such a manner that the hydrogen concentration in the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** has no peak, magnesium diffused into the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** reaches the active layer **103** easily. For this reason, the luminous efficiency is not improved. See the comparative example **1** (FIG. **6**) and the comparative example **5** (FIG. **7**). Accordingly, the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is required to have a hydrogen concentration distribution where the hydrogen concentration reaches a peak at the thickness t2.

On the other hand, hydrogen contained in the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** may be diffused by annealing or application of a voltage. Hydrogen reduces the luminous efficiency of the active layer **103**. For this reason, it is desirable that the thickness t2 is not less than 10 nanometers. More desirably, the thickness t2 is not less than 15 nanometers. Still more desirably, the thickness t2 is not less than 20 nanometers. It is desirable that the thickness t2 is not more than 80 nanometers. As described above, the thicker $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** has a greater resistance.

Desirably, the lower limit of the hydrogen concentration at the thickness t2 (i.e., at the peak) is 1.0×10^{17} atoms/cm^3. In a case where the hydrogen concentration at the thickness t2 (i.e., at the peak) is less than this value, the luminous efficiency decreases. This because an Mg—H bond is not formed sufficiently in the inside of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**, since the hydrogen concentration is too low.

Desirably, the upper limit of the hydrogen concentration at the thickness t2 (i.e., at the peak) is 1.0×10^{19} atoms/cm^3. In a case where the hydrogen concentration at the thickness t2 (i.e., at the peak) is more than this value, there are a great amount of hydrogen atoms near the active layer **103**. These great amount of hydrogen atoms are diffused into the active layer **103** by annealing to decrease the luminous efficiently.

(Fabrication Method)

Then, a method for fabricating a nitride semiconductor light-emitting element according to the present embodiment is described.

First, a substrate **101** is prepared. Desirably, the substrate **101** is a single-crystalline substrate formed of an m-plane GaN.

As shown in FIG. **8**, the substrate **101** may have an off-angle θ. The off-angle θ is formed between the normal direction **810** of the m-plane and the normal direction **820** of the principal plane. The off-angle θ may be more than 0 degrees and not more than 5 degrees. When the substrate **101** has an off-angle θ, the surface of the substrate **101** is stepwise microscopically. Desirably, the off-angle θ is equal to zero degrees. In other words, it is desirable that the substrate **101** does not have the off-angle θ.

Then, the n-type nitride semiconductor layer **102** is epitaxially grown on the substrate **101**. Furthermore, the active layer **103** is epitaxially grown on the n-type nitride semiconductor layer **102**.

The $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is epitaxially grown on the active layer **103**. The following procedures P1 and P2 are examples of the procedure where the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is epitaxially grown to have the peak of the hydrogen concentration at the thickness t2.

(Procedure P1)

FIG. **3** shows an example of the epitaxial growth profile according to the procedure P1.

First, trimethyl gallium (in FIG. **3**, referred to as "TMG"), trimethyl aluminum (in FIG. **3**, referred to as "TMA") and ammonia are supplied in the procedure P1 to form a lower part of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**. Trimethyl indium may also be supplied.

Subsequently, bis(cyclopentadienyl) magnesium (in FIG. **3**, referred to as "CP_2Mg") is also supplied to form an upper part of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** on the lower part of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**.

While the upper part of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is epitaxially grown, a growth temperature is gradually raised. In particular, the lower part of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is epitaxially grown under a growth temperature of 700-760 degrees Celsius.

The upper part of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is also epitaxially grown under a growth temperature of 700-760 degrees Celsius in the beginning. During this time, hydrogen atoms generated due to the thermal decomposition of bis (cyclopentadienyl) magnesium are incorporated into the growing $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**.

Subsequently, the growth temperature is gradually raised to 850-900 degrees Celsius. Desirably, the temperature rise rate falls within the range of 10-20 degrees Celsius/minute.

The higher the growth temperature is, the more molecular motion is activated. For this reason, the hydrogen atoms tend to be incorporated poorly into the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**.

As described above, while bis(cyclopentadienyl) magnesium is supplied under a low growth temperature of 700-760 degrees Celsius, hydrogen atoms are easily incorporated into the growing $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**. On the other hand, while bis(cyclopentadienyl) magnesium is supplied under a high growth temperature of 850-900 degrees Celsius, hydrogen atoms are poorly incorporated into the growing $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**. For this reason, as shown in FIG. **2**B, the peak of the hydrogen concentration is generated in the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**. In this way, provided is the hydrogen concentration distribution where the hydrogen concentration reaches the peak at the thickness t2. For more detail, see the examples.

(Procedure P2)

In the procedure P2, hydrogen is mixed with a carrier gas used when the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is epitaxially grown. An example of the carrier gas generally used is a nitrogen gas. In other words, a mixture gas of nitrogen and hydrogen is used as the carrier gas when the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is epitaxially grown. The ratio of hydrogen mixed with the carrier gas to nitrogen is adjusted during the epitaxial growth of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104**, and the hydrogen concentration distribution where the hydrogen concentration reaches the peak at the thickness t2 is obtained.

After the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is epitaxially grown, the p-type $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** is epitaxially grown. Furthermore, the p-type AlGaN layer **106** and a p-type GaN contact layer **107** are epitaxially grown. In this way, a nitride semiconductor stacking structure is obtained.

Subsequently, the nitride semiconductor stacking structure is subjected to a heat-treatment to activate the n-type dopant and the p-type dopant. A portion of the nitride semiconductor stacking structure is removed as shown in FIG. **1**, and the n-side electrode **109** and the p-side electrode **108** are formed. In this way, a nitride semiconductor light-emitting element is obtained.

EXAMPLES

The present invention is described in greater detail below with reference to the following examples.

In the following examples and comparative examples, a metalorganic chemical vapor deposition method (hereinafter, referred to as "MOCVD method") was used as an epitaxial growth method.

In the following examples and comparative examples, raw materials shown in the following Table 1 were used.

TABLE 1

Al raw materials	Trimethyl aluminum (TMA)
In raw materials	Trimethyl indium (TMI)
Ga raw materials	Trimethyl gallium (TMG)
Nitrogen raw materials	Ammonia
n-type impurities	Monosilane
p-type impurities	Bis(cyclopentadienyl) magnesium (CP_2Mg)

Example 1

The example 1 is described with reference to FIG. **1**. First, the n-type GaN substrate **101** having a principal plane of an m-plane was prepared.

Then, the n-type GaN layer **102** having a thickness of 2 micrometers was epitaxially grown on the n-type GaN substrate **101** at a growth temperature of 1,040 degrees Celsius. The n-type GaN layer **102** had a silicon concentration of 2.0×10^{18}cm^{-3}.

The multi-quantum-well layer **103**, namely, an active layer **103**, was epitaxially grown on the n-type GaN layer **102** at a growth temperature of 720 degrees Celsius. In greater detail, the multi-quantum-well layer **103** was formed by stacking three $In_xGa_{1-x}N$ layers (x=0.15) each having a thickness of 6 nanometers and four GaN layers each having a thickness of 12 nanometers alternately.

Subsequently, according to the epitaxial growth profile shown in FIG. **3**, the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** (x=0.01, y=0.008, z=0.982) was epitaxially grown on the active layer **103**. The $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** had a thickness of 75 nanometers. In other words, the thickness t1 was equal to 75 nanometers in the example 1.

The epitaxial growth of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** is described below in more detail.

First, trimethyl gallium, trimethyl aluminum and ammonia were started to be supplied onto the active layer **103** at flow rates of 4.3 micromol/minute, 0.16 micromol/minute, and 0.29 micromol/minute, respectively. The growth temperature was 740 degrees Celsius.

After 1,400 seconds had elapsed from the start of the supply of the raw material gas, bis(cyclopentadienyl) magnesium started to be supplied at a flow rate of 9.8×10^{-3} micromol/minute.

After 1,800 seconds had elapsed from the start of the supply of the raw material gas, the growth temperature was raised at a rate of 15 degrees Celsius/minute. After 2,400 seconds had elapsed from the start of the supply of the raw material gas, the growth temperature reached 890 degrees Celsius. After that, the growth temperature was maintained at 890 degrees Celsius. After 3,000 seconds had elapsed from the start of the supply of the raw material gas the growth of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** was completed.

The p-type $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** (x=0.20, y=0, z=0.80) was epitaxially grown on the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** at a growth temperature of 720 degrees Celsius. The $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** had a thickness of 20 nanometers. The $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** had a magnesium concentration of approximately 5.0×10^{18} cm^{-3}–1.0×10^{19} cm^{-3}.

The p-type $Al_{0.02}Ga_{0.98}N$ layer **106** was epitaxially grown on the p-type $Al_{x1}In_{y1}Ga_{z1}N$ layer **105** at a growth temperature of 890 degrees Celsius. The p-type $Al_{0.02}Ga_{0.98}N$ layer **106** had a thickness of 100 nanometers. The p-type $Al_{0.02}Ga_{0.98}N$ layer **106** had a magnesium concentration of 1.5×10^{19} cm^{-3}.

The p-type GaN contact layer **107** was epitaxially grown on the p-type $Al_{0.02}Ga_{0.98}N$ layer **106** at a growth temperature of 890 degrees Celsius. The p-type GaN contact layer **107** had a thickness of 50 nanometers. The p-type GaN contact layer **107** had a magnesium concentration of 1.0×10^{20} cm^{-3}. In this way, the nitride semiconductor stacking structure was obtained.

The nitride semiconductor stacking structure was subjected to annealing under a nitride atmosphere at a temperature of 850 degrees Celsius for 60 minutes to activate the p-type dopant, namely, magnesium.

Finally, the p-side electrode **108** and the n-side electrode **109** were formed. In this way, a nitride semiconductor light-emitting element according to the example 1 was obtained.

Then, the nitride semiconductor light-emitting element according to the example 1 was subjected to a SIMS analysis. FIG. **5** shows the SIMS analysis of the nitride semiconductor light-emitting element according to the example 1.

As is clear from FIG. **5**, the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** had a peak of the hydrogen concentration in the inside thereof. The thickness t2 was estimated to be approximately 58 nanometers from FIG. **5**.

Then, the light-emitting intensity of the nitride semiconductor light-emitting element according to the example 1 was measured with an Si photodiode (product of Hamamatsu Photonics, product number: PD S2281-01). Table 2 shows the results.

Example 2

An experiment similar to the example 1 was performed except that the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** had a thickness of 50 nanometers.

Example 3

An experiment similar to the example 1 was performed except that the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** had a thickness of 30 nanometers.

Comparative Example 1

An experiment similar to the example 1 was performed except that a GaN layer **104** was epitaxially grown instead of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** (x=0.01, y=0.008, z=0.982). FIG. **4**A shows the SIMS analysis result of the nitride semiconductor light-emitting element according to the comparative example 1.

FIG. **6** shows a SIMS analysis result in the comparative example 1 before the p-type dopant, namely, magnesium, was activated by annealing. As is clear from FIG. **6**, magnesium had been diffused into the GaN layer **104** before the p-type dopant was activated by the annealing. It would be obvious that magnesium was diffused into the active layer **103** after the p-type dopant had been activated by the annealing.

Comparative Example 2

An experiment similar to the example 1 was performed except that a GaN layer **104** was epitaxially grown instead of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** ($x=0.01$, $y=0.008$, $z=0.982$), and except that the GaN layer **104** had a thickness of 30 nanometers.

Comparative Example 3

An experiment similar to the example 1 was performed except that a GaN layer **104** was epitaxially grown instead of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** ($x=0.01$, $y=0.008$, $z=0.982$), and except that the GaN layer **104** had a thickness of 100 nanometers.

Comparative Example 4

An experiment similar to the example 1 was performed except that a GaN layer **104** was epitaxially grown instead of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** ($x=0.01$, $y=0.008$, $z=0.982$), and except that the GaN layer **104** had a thickness of 125 nanometers.

Comparative Example 5

An experiment similar to the example 1 was performed except that an $In_{0.008}Ga_{0.992}N$ layer **104** was epitaxially grown instead of the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** ($x=0.01$, $y=0.008$, $z=0.982$)

FIG. **7** shows a SIMS analysis result in the comparative example **5** after the p-type dopant was activated by annealing. As is clear from FIG. **7**, magnesium was diffused into the $In_{0.008}Ga_{0.992}N$ layer **104**.

The following Table 2 shows the results of the measurement of the examples and the comparative examples.

TABLE 2

	x2	y2	z2	Thickness of the layer 104	Optical power (microampere)
Example 1	0.01	0.008	0.982	75	178.4748
Example 2	0.01	0.008	0.982	50	185.6433
Example 3	0.01	0.008	0.982	30	181.2818
Comparative example 1	0	0	1	75	144.1216
Comparative example 2	0	0	1	30	134.4242
Comparative example 3	0	0	1	100	124.353
Comparative example 4	0	0	1	125	112.7791
Comparative example 5	0	0.008	0.992	75	110.0100

As is clear from Table 2, when the $Al_{x2}In_{y2}Ga_{z2}N$ layer **104** ($0<x2\leq 1$, $0\leq y2<1$, $0<z2<1$, $x2+y2+z2=1$) having a peak of the hydrogen concentration in the inside thereof is used, the optical power improves. This means that the luminous efficiency is improved.

Reference Example 1

An experiment similar to the example 1 was performed except that an n-type GaN substrate **101** having a principal plane of a c-plane was used instead of the n-type GaN substrate **101** having a principal plane of an m-plane. FIG. **4**B shows a SIMS analysis result of the nitride semiconductor light-emitting element according to the reference example **1**.

As is clear from FIG. **4**A and FIG. **4**B, compared to a conventional c-plane nitride semiconductor light-emitting element, a larger amount of magnesium contained in the p-type nitride semiconductor layer was diffused into the active layer **103** in the m-plane nitride semiconductor light-emitting element.

INDUSTRIAL APPLICABILITY

The nitride semiconductor light-emitting element according to the present invention is a nitride semiconductor light-emitting diode or a nitride semiconductor laser. A nitride semiconductor light-emitting diode is desirable. The nitride semiconductor light-emitting diode according to the present invention is installed in a lighting installation. Desirably, the nitride semiconductor light-emitting element according to the present invention is installed in an automotive headlight.

REFERENCE SIGNS LIST

101 substrate
102 n-type nitride semiconductor layer
103 active layer
104 $Al_{x2}In_{y2}Ga_{z2}N$ layer
104*a* first interface
104*b* second interface
105 $Al_{x1}In_{y1}Ga_{z1}N$ layer
106 p-type nitride semiconductor layer
107 p-type GaN contact layer
108 p-side electrode
109 n-side electrode
t1 thickness
t2 thickness
902 n-type nitride semiconductor layer
905 active layer
906 p-type AlGaN electron block layer
907 p-type nitride semiconductor layer
909 n-side electrode
910 p-side electrode

The invention claimed is:

1. A nitride semiconductor light-emitting element comprising:
an n-side electrode;
a p-side electrode;
an n-type nitride semiconductor layer electrically connected to the n-side electrode;
a p-type nitride semiconductor layer electrically connected to the p-side electrode; and
an active layer interposed between the n-type nitride semiconductor layer and the p-type nitride semiconductor layer; wherein
the p-type nitride semiconductor layer comprises an $Al_{x1}In_{y1}Ga_{z1}N$ layer ($0<x1\leq 1$, $0\leq y1<1$, $0\leq z1<1$, $x1+y1+z1=1$),
an $Al_{x2}In_{y2}Ga_{z2}N$ layer is interposed between the $Al_{x1}In_{y1}Ga_{z1}N$ layer and the active layer ($0<x2\leq 1$, $0\leq y2<1$, $0<z2<1$, $x2+y2+z2=1$),
the n-type nitride semiconductor layer, the active layer, the p-type nitride semiconductor layer, the $Al_{x1}In_{y1}Ga_{z1}N$ layer and the $Al_{x2}In_{y2}Ga_{z2}N$ layer are each formed of a non-polar or semi-polar nitride semiconductor,
the $Al_{x1}In_{y1}Ga_{z1}N$ layer has a higher bandgap than the $Al_{x2}In_{y2}Ga_{z2}N$ layer,

the $Al_{x2}In_{y2}Ga_{z2}N$ layer has a first interface and a second interface,

the first interface is located close to or in contact with the active layer,

the second interface is located close to or in contact with the $Al_{x1}In_{y1}Ga_{z1}N$ layer,

the $Al_{x2}In_{y2}Ga_{z2}N$ layer has a thickness t1,

the $Al_{x2}In_{y2}Ga_{z2}N$ layer has a hydrogen concentration distribution along its thickness direction in the inside thereof in such a manner that the hydrogen concentration is increased from the first interface to a thickness t2 (t2<t1), reaches a peak at the thickness t2, and is decreased from the thickness t2 to the second interface.

2. The nitride semiconductor light-emitting element according to claim **1**, wherein

the n-type nitride semiconductor layer, the active layer, the p-type nitride semiconductor layer, the $Al_{x1}In_{y1}Ga_{z1}N$ layer and the $Al_{x2}In_{y2}Ga_{z2}N$ layer are each formed of an m-plane nitride semiconductor.

3. The nitride semiconductor light-emitting element according to claim **1**, wherein the first interface is in contact with the active layer.

4. The nitride semiconductor light-emitting element according to claim **1**, wherein

the second interface is in contact with the $Al_{x1}In_{y1}Ga_{z1}N$ layer.

5. The nitride semiconductor light-emitting element according to claim **1**, wherein

the thickness t1 is not less than 20 nanometers and not more than 100 nanometers.

6. The nitride semiconductor light-emitting element according to claim **1**, wherein

the thickness t1 is not less than 30 nanometers and not more than 75 nanometers.

7. The nitride semiconductor light-emitting element according to claim **1**, wherein

a magnesium concentration at the first interface is not more than 1×10^{17} atoms/cm^3.

8. The nitride semiconductor light-emitting element according to claim **1**, wherein

the nitride semiconductor light-emitting element is a nitride semiconductor light-emitting diode.

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